

INTERACTIONS OF WILDFIRES AND FUELS
TREATMENTS PROXIMATE TO CRITICAL
HOTSPOTS OF RARE AND EXOTIC SPECIES IN
THE SOUTHWEST AND SOUTHERN ROCKY
MOUNTAINS

**Interactions of wildfires and fuels treatments proximate to
critical hotspots of rare and exotic species in the Southwest and
southern Rocky Mountains.**

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Phase II Final Report

submitted

by

Brett G. Dickson
Ph.D. Graduate Research Assistant
and
Barry R. Noon
Professor, Principal Investigator

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U.S. Department of Agriculture, Forest Service
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This final report includes the appended draft manuscript, *Mapping the occurrence and probability of large fire ignitions in northern Arizona*, which has been submitted to Ecological Applications for formal review. The manuscript is the main product for Phase II and provides the broader context for this research. This final report also includes analyses of the interaction between fire risk (i.e., ignition probability), rare (i.e., imperiled) taxa and exotic plant species (see below). Additionally, this report includes analyses supporting the placement of prescribed fire treatment units on the fire risk landscape characterized in the manuscript.

METHODS

For a 27065-km² area of northern Arizona (Figure 1), we examined the intersection between the probability of large fire ignition (Figure 2; see methods detailed in manuscript attached), summarized as 3 categories of fire risk: low, moderate, and high (Figure 3). For rare, threatened, and sensitive species listed as federal- or state-level imperiled by the Association for Biodiversity Information (ABI; v 9/2001), we mapped the occurrence of 199 detections in the region that included our study area (Figure 4). We used a 95% fixed kernel estimator to predict the probability of occurrence of imperiled species for those areas where records did not exist (see Figure 4). Similarly, we mapped the occurrence of 7429 detections of exotic plants obtained from the Southwest Exotic Plant Mapping Program (SWEMP; USGS v 2003; Figure 5). Again we used a 95% fixed kernel estimator to predict the probability of occurrence of exotic plants in those areas where records were unavailable (see Figure 5). We clipped each of the kernel estimates to the study area boundary prior to analysis. To characterize the interaction between fire risk

and the occurrence data (ABI and SWEMP), we overlaid the 3-category risk layer with each of the clipped kernel surfaces.

We buffered the locations of three prescribed fire treatment units to identify a spectrum of ignition probabilities and fire risk on our study area (Figure 6). We used a 10-km buffer in order to capture an area that reasonably characterized fire risk and ignition probability in the vicinity of a treatment unit.

RESULTS

Table 1. Probability of imperiled species occurrence in each of three fire risk categories, based on areas of overlap with the spatial extent of the 95% kernel estimate. Only areas with non-zero probability values were overlapped with the fire risk surface.

Risk category	Cell count	Mean probability	SD	Min. probability	Max. probability
Low	3671	0.439	0.239	0.010	0.950
Moderate	11891	0.435	0.232	0.010	0.950
High	8948	0.437	0.224	0.010	0.950

Table 2. Probability of exotic plant species occurrence in each of three fire risk categories, based on areas of overlap with the spatial extent of the 95% kernel estimate*. Only areas with non-zero probability values were overlapped with the fire risk surface.

Risk category	Cell count	Mean probability	SD	Min. probability	Max. probability
Low	1340	0.274	0.189	0.010	0.950
Moderate	3953	0.260	0.184	0.010	0.950
High	1411	0.195	0.144	0.010	0.950

* The smaller spatial extent of the of the kernel estimate also reflects fewer areas where exotic plants were sampled or detected in the southwestern portion of the study area (see Figure 5).

Table 3. Probability of large fire ignition (human and natural caused) within 10km-buffer of each of three prescribed fire treatment units. Statistics for the 27065-km² study area are also shown.

Treatment unit	Mean probability	SD	Min. probability	Max. probability
Kendrick	0.0316	0.0189	0.0123	0.0737
Imax	0.0273	0.0135	0.0177	0.0737
Lakeside	0.0253	0.0096	0.0123	0.0737
Study Area	0.0331	0.0197	0.0123	0.0737

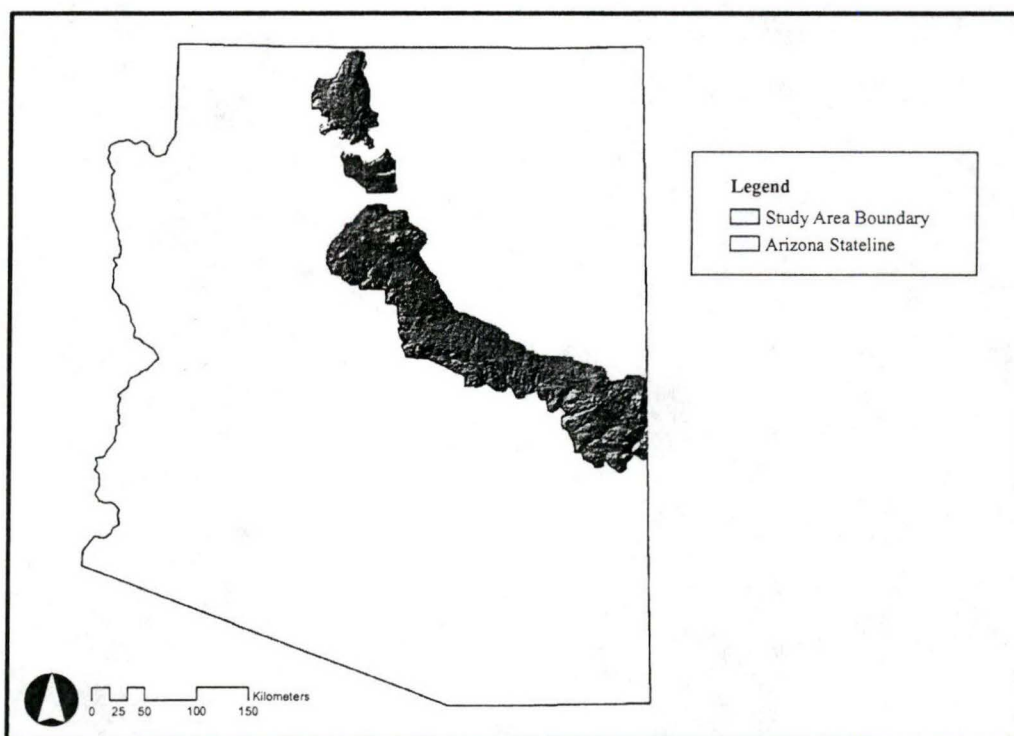


Figure 1. The 27065-km² study area used to examine the relationship between large fire ignition occurrence (1 April to 30 September, 1996-2000), imperiled species and exotic plant occurrence, and fire risk.

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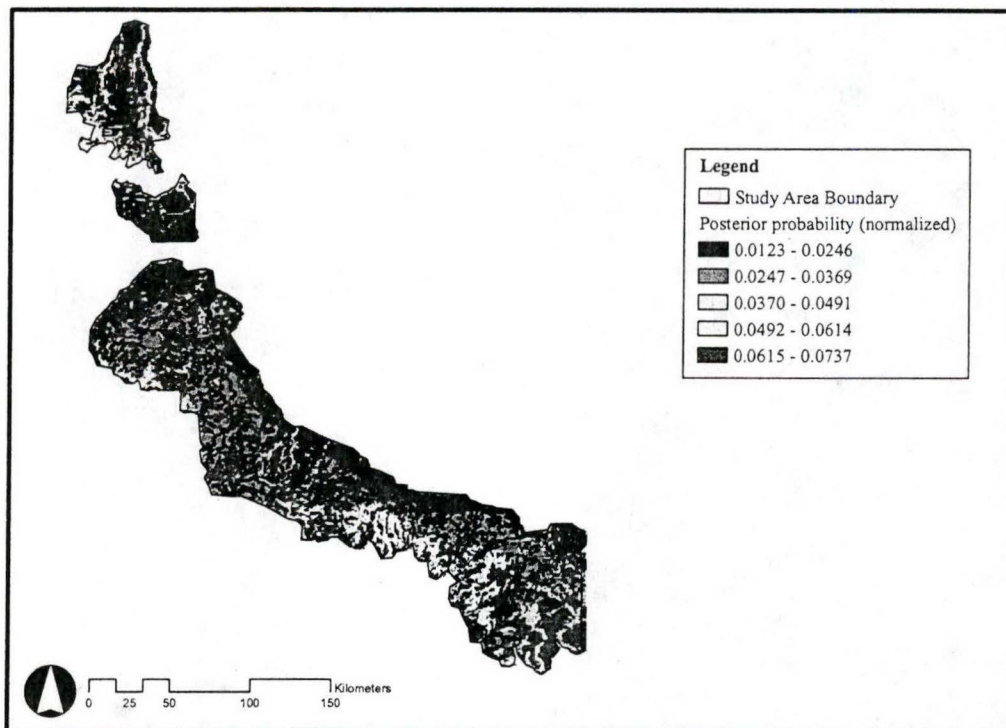


Figure 2. Normalized posterior probability of occurrence for all ($n = 203$) large fire ignition types (human and lightning caused) on the study area, 1 April to 30 September, 1986-2000.

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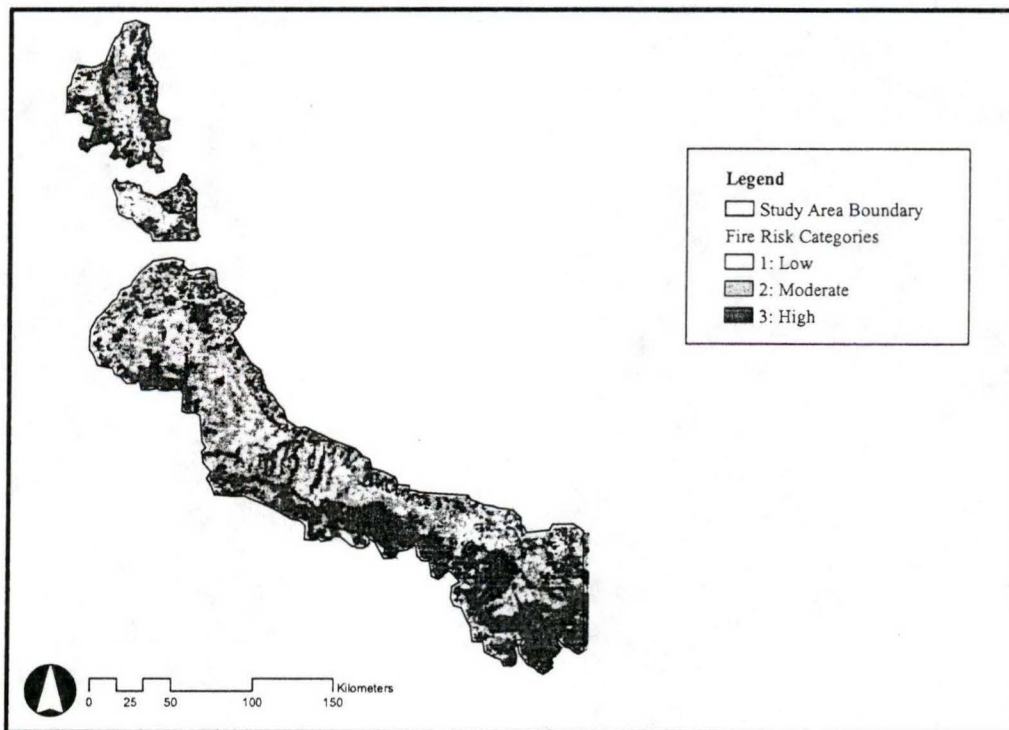


Figure 3. Quantile categorization of fire risk using normalized posterior probability of occurrence for all ($n = 203$) large fire ignition types (human and lightning caused) on the study area, 1 April to 30 September, 1986-2000.

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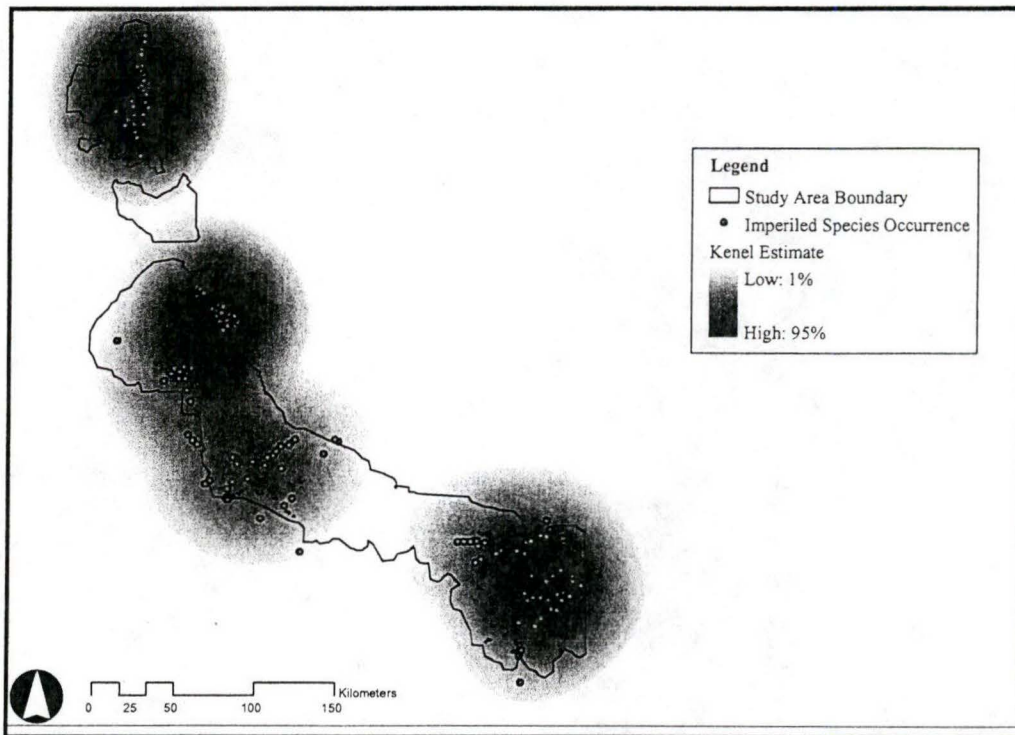


Figure 4. Occurrence of federal- and state-listed imperiled species ($n = 199$, and within 10km buffer) And 95% fixed kernel estimator predicting probability (low to high) of occurrence of imperiled species across region that includes study area.

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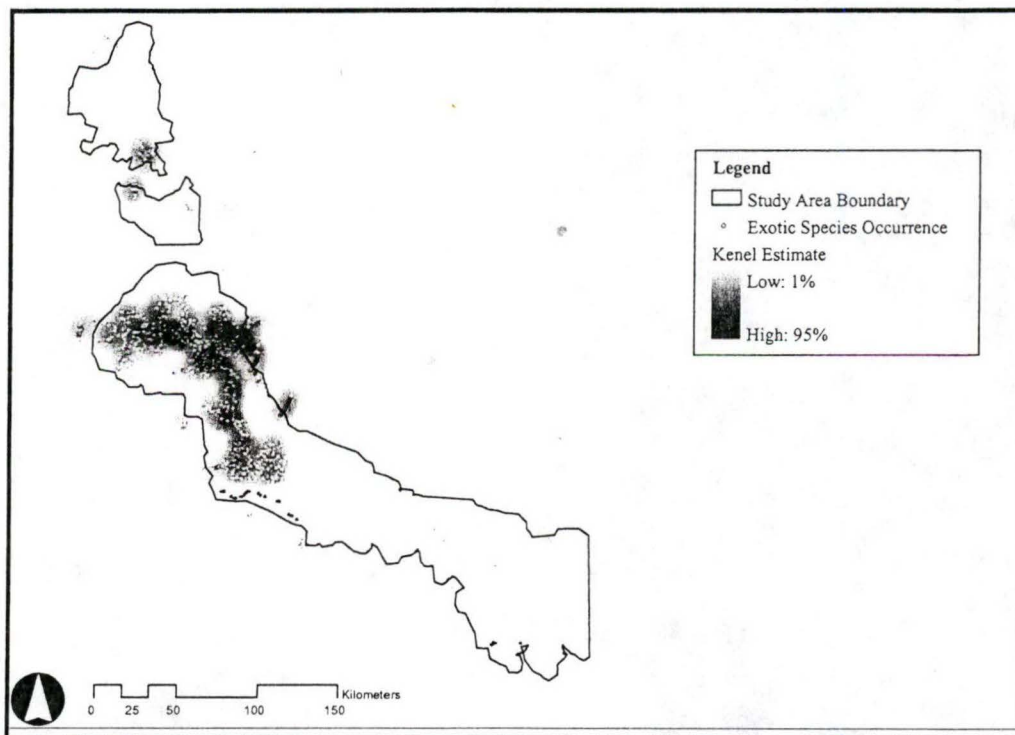


Figure 5. Occurrence of SWEMP-listed exotic plant species ($n = 7429$, and within 10km buffer) and 95% fixed kernel estimator predicting probability (low to high) of occurrence of exotic plant species across region that includes study area.

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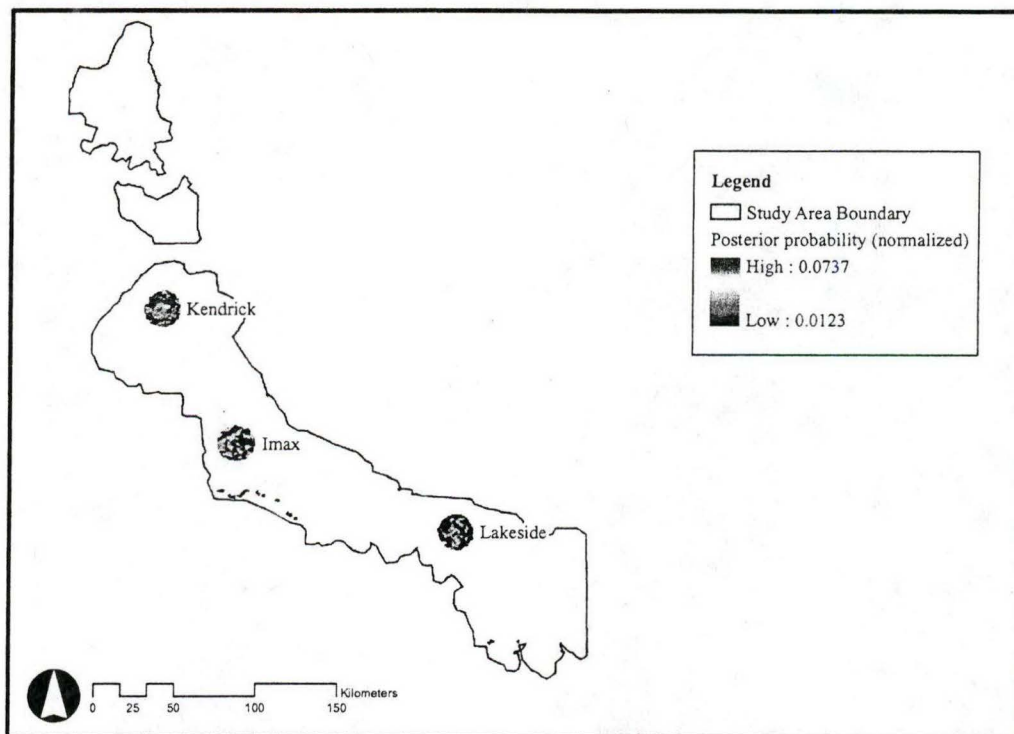


Figure 6. Posterior probability of large fire ignition on area (buffered using 10km radius) surrounding each of the three prescribed fire treatment units. Only treatment units located in AZ are named and displayed. Buffered area is approximately 386km².

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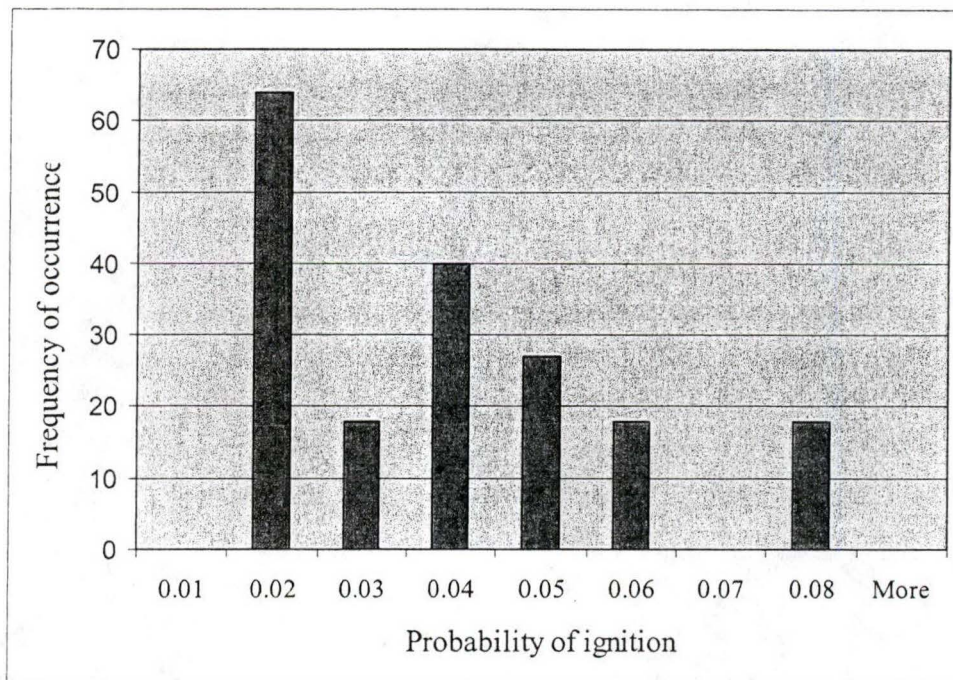


Figure 7. Frequency of imperiled species occurrence for 9 ignition probability classes.

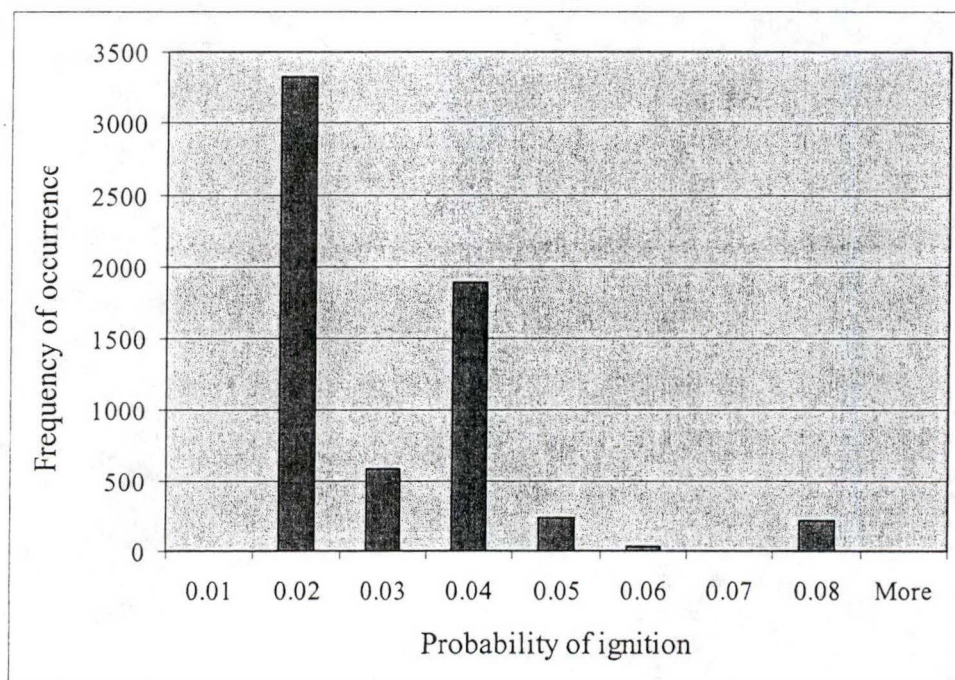


Figure 8. Frequency of exotic plant occurrence for 9 ignition probability classes.

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Brett G. Dickson

Department of Fishery and Wildlife Biology

Colorado State University

Fort Collins, CO 80523-1474

970-491-3535; FAX 970-491-5091; E-mail dickson@cnr.colostate.edu

MAPPING THE OCCURRENCE AND PROBABILITY OF LARGE FIRE IGNITIONS IN NORTHERN ARIZONA

BRETT G. DICKSON,^{1,2,3} YAGUANG XU,² JOHN W. PRATHER,²

HAYDEE M. HAMPTON,² ETHAN N. AUMACK,² and THOMAS D. SISK²

¹*USDA Forest Service, Rocky Mountain Research Station, 2500 South Pine Knoll Drive, Flagstaff,
Arizona, 86001, USA and Department of Fishery and Wildlife Biology, Colorado State University,
Fort Collins, Colorado, 80523, USA*

²*Lab of Landscape Ecology and Conservation Biology, Center for Environmental Science and Education,
Northern Arizona University, Flagstaff, Arizona 86011, USA*

³ Corresponding author. Email: dickson@cnr.colostate.edu

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25 *Topographic roughness, Weights of evidence, Wildland fire.*

(Swetnam and Betancourt 1998). During this period, there are isolated, but often frequent, lightning strikes induced by dry thunderstorms (Allen 2002). The maximum area burned usually occurs in June, while the maximum number of lightning-caused fires usually occurs in July during the summer monsoon (Swetnam and Betancourt 1998). In the region that includes northern Arizona and western New Mexico, 60-70% of forest fires are ignited by lightning, compared to approximately 20% nationwide. This area leads the nation in the average number of lightning-caused fires and average amount of National Forest area burned by these fires each year (Barrows 1978). Historically, most large fires in the Southwest were associated with broad-scale climate factors, or controls, such as El Niño-Southern Oscillation (ENSO) patterns and the persistence of drought conditions (Swetnam and Betancourt 1990, see Allen 2002). However, retrospective studies of historical fire events suggest an increase in the number of large human- and lightning caused fires since the beginning of the 20th century (Swetnam 1990). For the period 1992-2003, the Southwest region (Arizona, New Mexico, and West Texas) experienced an annual average of 3059 human-caused fires and 2613 lightning-caused fires, burning an annual average of 91906 ha and 84900 ha, respectively (USDA Forest Service 2004). In addition to climatic and human-induced changes to the environment, many current wildland fire events occur as a result of human negligence or deliberate intent (U.S. NIFC 2003). According to the U.S. Forest Service, human activity results in the ignition of more than 90 percent of all wildland fires on public lands (USDA Forest Service 1998, 2000). An historical increase in the size of human-caused fires may be due, in part, to an increase in the number of roads and improved access to remote forested locations (Swetnam 1990, Cardille et al. 2001, see DellaSala and Frost 2001). In spite of

and 4) quantify the relationships between fire ignition source, landscape features, and patterns of ignition occurrence.

Methods

Study area

Our 27065-km² study area included the ponderosa pine-dominated forest regions of northern Arizona, USA (Fig. 1). In general, these forests occurred in three distinct regions: a region that included the Kaibab Plateau to the north of the Grand Canyon (area = 3390 km²); the area to the south of the Grand Canyon and northwest of Flagstaff, Arizona (1418 km²); and an area that extended from the Western Mogollon Rim Plateau, east to the New Mexico border (22257 km²). Other common tree species on the study area included quaking aspen (*Populus tremuloides*) and Gambel's oak (*Quercus gambelii*). Elevations across the study area ranged from approximately 1520 to 3850 m on Humphrey's Peak, the highest point in Arizona. Because the ponderosa pine-dominated vegetation zones generally occurred above 1520m, we constrained the borders of our study area using this minimum elevation threshold. We also constrained the study area boundary by excluding slopes > 45°, since forest-dominated vegetation types do not typically occur in these areas. Mean annual precipitation and mean annual maximum temperature ranged from 58.7 cm and 14.3 °C, respectively, at higher elevations on the north end of the study area (Jacob Lake, 1971-2000, elev 2420 m) to 52.6 cm and 21.8 °C, respectively, at lower elevations on the south-central end of the study area (Payson Ranger Station, 1971-2000, elev 1520 m; US WRCC 2004). Across most of the study area, approximately 65% of precipitation fell as snow during the winter months (USDA

to be influenced more by landscape-level variables than by the immediate ignition environment. In addition, while most ignitions result in fires < 1 ha in size, those fires that do reach 20 ha are likely to grow larger. For example, in Colorado <5% of fires reach 20 ha in size, but those that do have a 46% chance of reaching 100 ha and an 18% chance of reaching 400 ha in size (Neuenschwander et al. 2000). We considered only those ignitions that occurred between 1 April and 30 September, the season that captures the driest months in the region and the monsoonal storm patterns, during which lightning strikes are most common (Swetnam and Betancourt 1998). This period also includes those months when forest use and recreational activities are most common. We excluded records on human-caused prescribed fires that were contained to planned boundaries. To avoid including duplicate occurrence records in our database, we discarded an ignition when attribute information for month, day and year were identical to another ignition within 1000 m. We converted each remaining ignition record in the database to a point feature in a fire occurrence data layer and identified the Universal Transverse Mercator (zone 12, North American 1983 datum) northing and easting coordinate using a geographic information system (GIS; ArcGIS v8.3, ESRI, Redlands, California, USA). For both LCI and HCI, we assessed correlations between monthly ignition frequency and total area burned using Spearman's rank order correlation coefficient (r_s = test statistic).

Spatial input maps

For our analyses, we developed 8 spatial data layers, or input maps, that included information on physiographic, biotic, climatic, spatial, and human factors that were likely to influence the ignition of fires. Specifically, we created unique input maps for

and slope, the value of each 1-km² cell in the final map was calculated as the mean value of all 90-m cells contained within that 1-km² cell (a “focalmean” moving window operation in the GIS; see Fig. 1). Using a quantile classification, we then classified elevation and slope into areas of high- or low-elevation, and high- or low-slope, respectively. For aspect, we assigned each 90-m cell an “aspect score” value based on that cells relationship with the regional prevailing wind direction in the fire season (225° or SSW; NOAA 1998); cells with aspects between 195° and 255° were assigned a value of two, cells between 135° and 195°, or between 255° and 315°, a value of one, and all other cells were assigned a value of zero. The final aspect score value for each 1-km² cell was the sum of all 90-m cell aspect scores values contained within that cell (a “focalsum” moving window operation; Fig. 3A). We classified aspect score as high or low, based on landscape area using the quantile method. To derive our terrain roughness map, we calculated the standard deviation for the elevation of all 90-m cells in a 3 x 3 neighborhood. The final value for each 1-km² cell was determined by summing the standard deviation values of all 90-m cells within that cell (“focalsum” moving window operation; Fig. 3B). Low to high class numbers indicate lower to higher degrees of topographic roughness.

Because different forest types have fire regimes that differ in frequency and intensity (Swetnam and Baisan 1994), it was necessary to develop an input map of dominant forest vegetation on our study area. We first obtained a 30-m resolution land cover map from the USGS National Land Cover Dataset (USGS 1992). Since this map represents only a coarse classification of dominant forest types (e.g., evergreen forest), we supplemented this map with Enhanced Thematic Mapper (ETM; 30-m resolution)

(Fig. 3F). These arbitrary domains were equal in shape and extent and did not capture equal-area proportions of the study area. We tested the hypothesis of complete spatial randomness in the ignition occurrence data by buffering our study area to 10 km and using an edge corrected point pattern analysis (R = test statistic; Clark and Evans 1954, Bailey and Gatrell 1995).

To minimize the influence of boundaries on the value assigned to cells at the perimeter of the study area, we computed the values of all input map cells within the study area, plus a 1-km buffer. We clipped all input maps to the study area boundary prior to any analyses.

Weights-of-evidence modeling

To quantify broad-scale patterns of fire ignition probability, we used weights-of-evidence (WOE) modeling. Weights of evidence is a Bayesian method of event prediction using known locations of event occurrence. We chose this method because it is spatially explicit, robust to small sample sizes at large spatial scales, and easy to implement and interpret. The approach was originally used in medical diagnoses (Spiegelhalter and Knill-Jones 1984, Spiegelhalter 1986), but has recently been extended to the prediction and spatial analysis of mineral deposits (Agterberg 1989, Raines and Mihalasky 2002), archaeological sites (Hansen 2000), fossilized packrat middens (Mensing et al. 2000), and plant migrations (Lyford et al. 2003). The method has not previously been applied to the prediction of fire ignition patterns. Weights-of-evidence models use the spatial location of known occurrence points to determine coefficients for a set of categorical input maps (Bonham-Carter et al. 1989). For each analysis unit, or unit cell, these coefficients

$$O(D|E_i) = O(D) \frac{P(D|E_i)}{P(\overline{D}|E_i)}.$$

According to the above equations and Bayes' rule, we derived the following equations

$$O(D|E_i) = O(D) \frac{P(E_i|D)}{P(E_i|\overline{D})}, \text{ and}$$

$$\ln(O(D|E)) = \ln(O(D)) + \ln\left(\frac{P(E_1|D)}{P(E_1|\overline{D})}\right) + \dots + \ln\left(\frac{P(E_n|D)}{P(E_n|\overline{D})}\right).$$

The weight for evidence pattern, i , where $j = 1, 2, \dots, n$, is defined by the expression

$$\ln\left(\frac{P(E_i|D)}{P(E_i|\overline{D})}\right).$$

Thus, if E_i is present, the weight is

$$W_j^+ = \ln\left(\frac{P(E_i|D)}{P(E_i|\overline{D})}\right),$$

and if E_i is absent, the weight is

$$W_j^- = \ln\left(\frac{P(\overline{E_i}|D)}{P(\overline{E_i}|\overline{D})}\right).$$

Therefore, the log odds of a unit cell's posterior probability can be obtained by adding weights W^+ or W^- for presence or absence of each input map unit cell to the log odds of the prior probability, expressed as

$$\ln(O(D|E_i)) = W_0 + W_1^+ (\text{or } W_1^-) + \dots + W_n^+ (\text{or } W_n^-) = \sum_{j=0}^n W_j^k,$$

where k represents a positive (presence) or negative (absence) weight. Finally, the unit cell posterior probability, $P(D|E_i)$, is obtained from the logit equation

$$P(D|E_i) = \frac{\exp(\ln(O(D|E_i)))}{1 + \exp(\ln(O(D|E_i)))},$$

Total uncertainty in the posterior probability maps was estimated as

$$\sigma^2(TOTAL) = \sigma^2(WEIGHTS) + \sum_{j=1}^n \sigma_j^2(MISSING).$$

For the final uncertainty maps, we calculated a studentized uncertainty statistic for each cell as

$$P_{post} / \sigma_{TOTAL}.$$

Values of this ratio < 1.960 represented cells with significant uncertainty ($\alpha = 0.05$; Bonham-Carter et al. 1989).

We used the Arc-SDM (Kemp et al. 2001) spatial data modeler extension to ArcView v3.3 (ESRI, Redlands, California, USA) to conduct all WOE calculations and analyses. We modeled all fire ignition types, and then we modeled lightning-caused fire ignitions alone. Because too few (< 100) records for large HCI fires were present in our final database, we did not model these ignitions separately.

Results

Fire ignition occurrence

Between 1 April and 30 September, 1986-2000, 203 fire ignitions occurred within the boundaries of our study area (Table 1, Fig. 2). Of this total, 136 (67%) ignitions were lightning caused. For LCI and HCI combined, total area burned during the period was 101751 ha. Fires due to lightning burned more than 4 times the area burned by HCI (83055 vs. 18696 ha). The greatest number of fires occurred in 2000 ($n = 26$) and the greatest amount of area was burned occurred in 1996 (38140 ha). Of this total area, 32674 ha (86%) burned as a result of LCI. The greatest average amount of area burned

Considering all fire ignition occurrences, we calculated a prior probability of
 0.008 for our period of study. The pairwise test of the assumption of conditional
 independence for the ponderosa pine-dominated forest and precipitation input maps was
 not satisfied in the analysis of all fire ignitions ($\chi^2 = 41.6$, d.f. = 2). Therefore, we
 combined these maps (Bonham-Carter et al. 1989, Agterberg and Cheng 2002) and
 evaluated a new input map with 2 binary classes: presence of ponderosa pine-dominated
 forest or high precipitation (Forest_Precip; class 1) and absence of both (class 2). New
 tests for all of the input maps satisfied the conditional independence assumptions. At the
 resolution and extent (spatial and temporal) of our input maps, the probability of a fire
 due to all ignition types was most influenced by topographic roughness, followed by road
 density, and Forest_Precip (Table 3). Elevation, aspect, and spatial domain were not
 important predictors of occurrence in this model ($C < 0.300$, $P > 0.05$). For this analysis,
 we identified 3 topographic roughness classes for which absolute contrast values were $\geq$
 0.300 and statistically significant. High topographic roughness (class 3) was the best
 predictor of fire ignition occurrence ($C = 0.912$), and was also characterized by the
 highest positive weight ($W^+ = 0.511$). Low road density (class 2) and Forest_Precip were
 also good predictors of occurrence. Because they indicated areas with less chance of fire
 ignition, areas of moderate (class 2, $C = -0.538$) and low (class 1, $C = -0.572$)
 topographic roughness were also considered important predictors.

Our WOE model for all ignition types summed the weights of the topographic
 roughness, road density, and Forest_Precip maps. The conditional probability of a fire
 occurrence ranged between 0.012 and 0.074 (mean = 0.031, SD = 0.016; Fig. 4A). The
 corresponding uncertainty for these probabilities ranged between 0.003 and 0.021 (mean

all ignition types, fewer ignitions in the WOE analysis of LCI provided for greater uncertainty in more cells (Fig. 5B). However, very few ($n = 34$) cells had studentized uncertainty values < 1.960 .

Discussion

Fire ignition occurrence

Between 1 April and 30 September, 1986-2000, fire ignitions on our study area were predominantly caused by lightning strikes and varied greatly in annual frequency and total area burned. Most (71%, $n = 97$) of these occurrences burned a total area ≤ 200 ha per year. Consistent with an earlier figure reported by Barrows (1978) for all natural-caused fires, we found that 67% of all fires on our study area were due to LCI. However, a relatively small number of these fires represented a substantial fraction of the total yearly and monthly areas burned. In 1996, the driest recorded calendar year on our study area, 3 fires burned a total of 28326 ha, or 87% of the total area burned due to lightning-caused fires that year (34% of the total for our 15 year period of study). Although it is not uncommon for only a few natural fires to burn extensive areas, our results for LCI reinforce concerns about more recent and drastic changes in forest structural characteristics in southwestern forests due to decades of fire suppression (Grissino-Mayer and Swetnam 2000, Allen et al. 2002, Covington 2003, Schoennagel et al. 2004).

During our period of study, we observed a decrease in the frequency of HCI, but an increase in the total area burned annually: 10 ignitions burned 830 ha in 1989, 9 ignitions burned 1575 ha in 1993, 4 ignitions burned 5467 ha in 1996, and 3 ignitions burned 6422 ha in 2000. Even though they occur infrequently, fires due to HCI have the

native plants and wildlife (e.g., birds) of the Southwest are at different phenological and life-history stages, respectively, in May than in June.

Allen (2002) concluded that, prior to 1900, the impact of human-induced fire was probably muted by frequent lightning fires, and that modern fire suppression efforts are having a large effect on southwestern fire regimes. Our results suggest that patterns of human-caused ignition in the Southwest, combined with human-induced change in forest structure, may be shifting the historic fire regime towards one with larger and more frequent fire events.

Fire ignition probability

We identified significant interactions between landscape features and landscape-scale patterns of large fire ignition occurrence. Predictors of fire ignition differed by ignition-type analysis (LCI vs. all), although highly ranked predictors were similar for both WOE analyses. For the most important predictors of fire ignition, we observed higher contrast values and weights for LCI than for all ignitions combined. Patterns observed in our analysis of all ignitions were likely dampened by the inclusion of HCI, which were highly variable in their timing, location, and extent. Additionally, because our analyses considered only one anthropogenic input map (road density), we were unable to account for the range of unique factors that likely influence patterns of HCI (e.g., proximity to urban centers, human density). A qualitative examination of patterns for all ignitions combined revealed that fires due to HCI are more likely to occur in areas of high road density, while fires due to LCI are more likely to occur in areas of low road density.

local climate, vegetation, and the spatial distribution of fuels (Whelan 1995).
Topographically complex areas can facilitate or impede fire ignition and behavior
(Whelan 1995, Graham et al. 2004). Rate of spread may increase with steeper slopes
because flames are angled closer to the ground and because the process of heat
convection within the fire produces supplemental wind effects (Whelan 1995, DeBano et
al. 1998). Where fuel loads are high or continuous, rate of spread and fireline intensity
increase as adjacent fuels are pre-heated and combust. These fire behaviors are strongly
influenced by topography (Whelan 1995, DeBano et al. 1998).

Fire suppression efforts in areas of remote and rough terrain are constrained by
slower reporting and response times and limited access. The influence of high
topographic roughness on the occurrence of large fires may be exaggerated by this fact.
Although the road density and topographic roughness input maps were not strongly
correlated (correlation coefficient = 0.04), areas with low road densities were highly
ranked by each WOE analyses. If low road densities in rugged areas facilitate the
transition of an ignition into a large fire event, then the role of limited road access for
suppression efforts in these areas should be recognized in the management of the present
fire regime. This is not to suggest, however, that fire occurrence could be reduced by the
construction of new roads in areas more prone to ignition; more roads in these areas will
allow increased access by humans, which is likely to result in an increase in fires
(Swetnam 1990, Brown et al. 2004). In the upper Midwest, where most ignitions are due
to humans, the probability of occurrence of a larger fire has been found to be positively
correlated with road density (Cardille et al. 2001), and in the San Jacinto mountains of
California, fires are more likely to occur near roads (Chou et al. 1993). An increase in

development (see Dahms and Geils 1997), could further modify the forested landscape in ways that facilitate large fire events.

Although statistically significant, areas with high precipitation did not rank as a dominant influence on total ignition patterns. The coarse resolution (spatial and temporal) of our precipitation input map may have resulted in low power to detect relationships. In the Southwest, lightning strikes and high levels of precipitation are often significantly positively correlated (Gosz et al. 1995). However, our results indicate that fire ignitions due to lightning were not correlated with precipitation during the period of our analysis. On our study area, high levels of precipitation likely contribute to increased fuels in ponderosa pine-dominated stands. For example, Swetnam and Betancourt (1998) identified a strong relationship between the recent growth of southwestern trees and exceptionally high amounts of annual precipitation since 1976. In response to a dry period that follows a sequence of extremely wet seasons, accumulated fuels can contribute to exceptionally large fire events (Swetnam and Betancourt 1998, Grissino-Mayer and Swetnam 2000). Because our ignition data span a period of 15 years, the role of longer-term patterns of climatic oscillation (e.g., ENSO) and periodic drought is not well represented by our analysis and interpretation. Nevertheless, many of the major controlling factors in our models are topographic in nature (roughness, aspect), and these may be more important in determining local patterns of fires than climatic effects, which are likely to affect the entire region in a similar fashion.

Aspect score was statistically significant in our WOE analysis of LCI, but was not a highly-ranked predictor variable. Our WOE analyses aspect-score method incorporated the role of the prevailing wind direction in the quantification of aspect importance.

The number of fire ignitions in each spatial domain provided insufficient evidence for coarse-scale, spatial clustering of these events. At a regional scale, Díaz-Avalos et al. (2001) and Preisler et al. (2004) each identified the importance of spatial location in estimating the probability of ignition occurrence in Oregon. However, our more coarse method of characterizing spatial location in the WOE models was unable to detect a statistically similar pattern. More qualitative evaluation of these data indicated moderate patterns of regional occurrence by ignition type: 35% ($n = 47$) of all LCI and 25% ($n = 17$) of all HCI occurred in the southeastern domain (domain 6; see Fig. 2). Forty of these LCI occurred within just a 26-km radius. Thirty percent ($n = 20$) of all HCI occurred in the west-central domain (domain 5), the region of the study area that includes the city of Flagstaff, compared to 21% ($n = 29$) of all LCI. Apparent clustering of LCI in the southeastern domain occurred in the most rugged and remote portion of the study area. This subregion included large portions of the Apache-Sitgreaves National Forest only lightly populated by humans. Thus, factors such as the time lag in suppression efforts due to delays in reporting and response may result in a larger number of fires than in other subregions.

The nonrandom distribution of fire ignition occurrence on our study area indicated more local patterns of spatial clustering in these events. On average, the nearest-neighbor distance between all ignition and LCI types was 4 km and 5 km, respectively. Using point pattern analysis, Podur et al. (2003) also detected significant local-scale clustering in lightning strikes in Ontario and determined these patterns to be principally related to localized phenomena. Our results suggest that ignition clustering

(*sensu* Heyerdahl et al. 2001), such as those exerted by regional climatic patterns at human time scales, may not currently affect the regional fire regime to the extent they did historically. Instead, topographic roughness, combined with reduced access to these areas, and coupled with the spatial distribution of increased fuels at the landscape scale, appear to be the primary controls (the “bottom-up” controls posited by Heyerdahl et al. 2001) on the present fire regime in this region.

Locating treatments in remote and rugged areas is strategically difficult and prescribed fires in more accessible locations appears to be a reasonable management alternative so long as human communities are protected (Allen et al. 2002, Dombeck et al. 2004). However, fire behavior and the restoration of fire regimes in these locations deserves greater research attention. Recent research has assessed the potential to minimize fire threat to populated areas by strategically placing forest treatments and fuel breaks around communities (see Graham et al. 2004). Our results suggest that treatments intended to reduce fire threat around communities should first target areas bordering rough terrain, thus providing a “firebreak” in areas where fires are more likely to spread. Because fires tend to ignite in rugged and remote areas, fire suppression efforts in neighboring populated areas should be evaluated in the context of public acceptance of fire as a natural disturbance process.

Fire risk is defined as the probability of a fire occurring in a given area and maps of fire risk are usually based on probability of ignition or fire spread (see Sampson et al. 2000). Our novel and spatially explicit methods provide a tractable approach to modeling and quantifying ignition probability, and our map outputs can be useful in the planning and coordination of community and/or regional efforts to identify areas at greatest risk.

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Table 2. Monthly number of occurrences, total area (ha), and mean ($\pm$ SD) area (ha) burned for all ($n = 203$) fire ignition types on the study area, 1 April to 30 September, 1986-2000. Summary statistics derived from database of large (≥ 20 ha in extent) fire ignitions occurring on federal lands.

Month	All ignitions			Lightning-caused ignitions			Human-caused ignitions		
	No. of occurrences	Total area burned	Mean area burned	No. of occurrences	Total area burned	Mean area burned	No. of occurrences	Total area burned	Mean area burned
April	18	4546	253 (488)	7	2155	308 (500)	11	2391	217 (502)
May	27	16466	610 (1456)	10	5520	552 (1094)	17	10947	644 (1664)
June	57	52587	923 (2691)	33	50305	1524 (3431)	24	2281	95 (142)
July	51	21468	421 (1222)	40	19255	481 (1355)	11	2213	201 (487)
August	28	2304	82 (99)	27	2041	76 (95)	1	263	263
September	22	4380	199 (314)	19	3779	199 (333)	3	601	200 (188)
Mean of means	34 (16)	16959 (19063)	415 (310)	23 (13)	13843 (19001)	523 (521)	11 (9)	3116 (3945)	270 (191)
Total	203	101751		136	83055		67	18696	

Table 4. Input maps significantly correlated with the known occurrence of lightning-caused ($n = 136$) large fire ignitions on the study area, and their associated WOE statistics, for the period 1 April to 30 September, 1986-2000. Because of the inverse relationship between binary value input map classes, we report only those class results for which values of C were positive. Input map importance in predicting large fire ignition occurrence is ranked from top (high) to bottom (low) according to the value of C .

Input map	Class	No. of occurrences	W^+	$SD(W^+)$	W^-	$SD(W^-)$	Contrast (C)	$SD(C)$	student(c)*
Roughness	3	86	0.647	0.108	-0.599	0.142	1.246	0.178	6.988
Road density	2	91	0.385	0.105	-0.499	0.149	0.884	0.183	4.839
Forest vegetation	1	96	0.182	0.102	-0.337	0.158	0.519	0.189	2.752
Aspect score	2	83	0.155	0.110	-0.203	0.138	0.358	0.176	2.030
Roughness	2	30	-0.433	0.182	0.166	0.097	-0.599	0.207	-2.891
Roughness	1	20	-0.805	0.224	0.240	0.093	-1.045	0.243	-4.310

* Values statistically significant at $\alpha = 0.05$ (> 1.96 , < -1.96).

FIG. 1

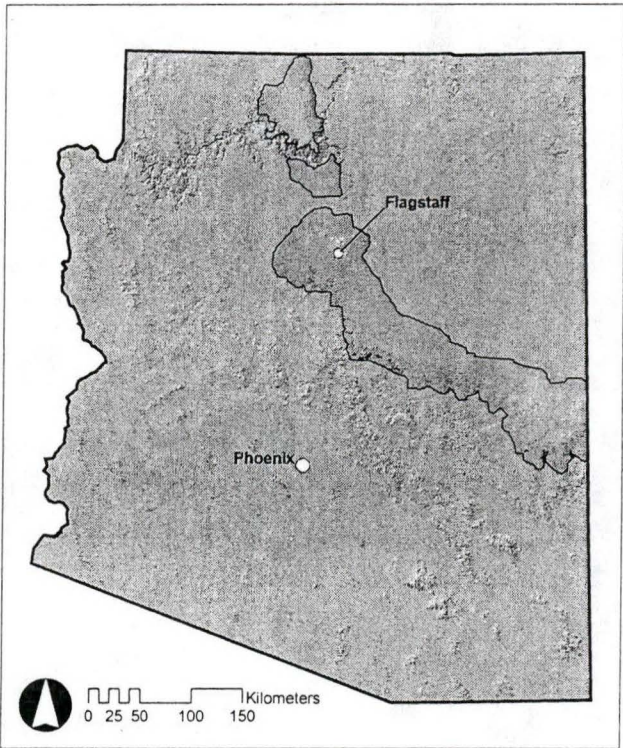


FIG. 3

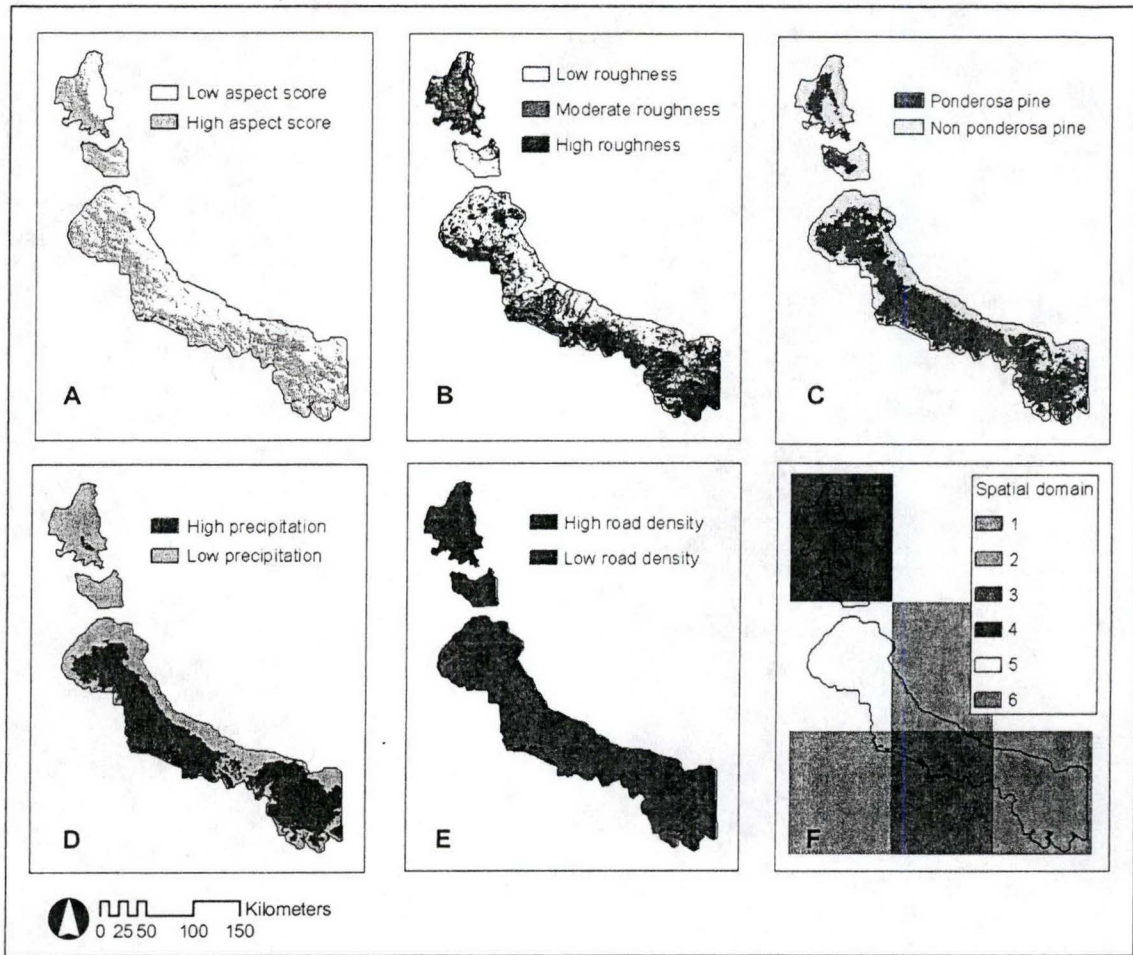


FIG. 4

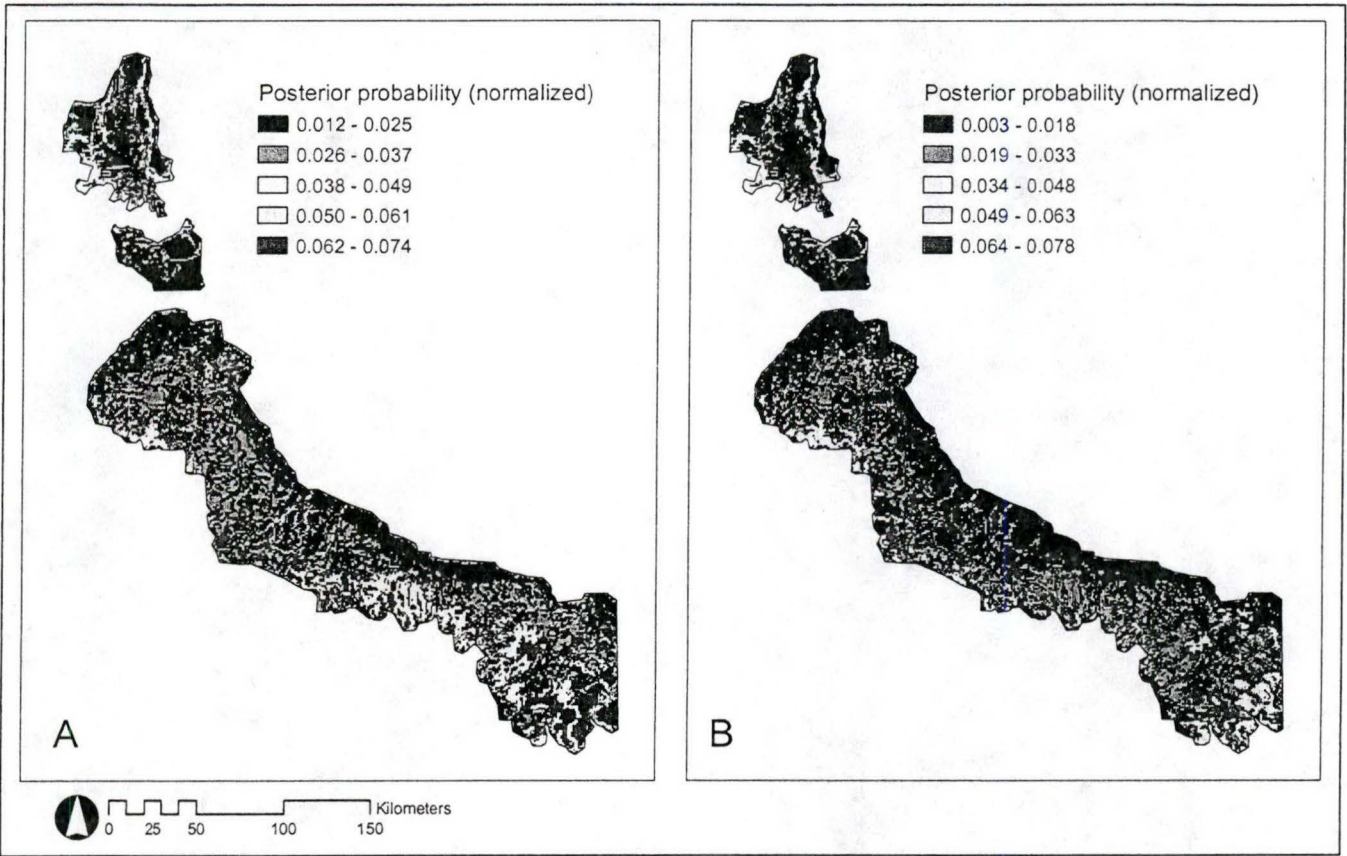


FIG. 5

